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CRACK GROWTH MONITORING IN COMPOSITE MATERIALS USING EMBEDDED OPTICAL FIBER BRAGG GRATING SENSOR

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ABSTRACT

In this paper a novel method to assess a crack growing/damage event in fiber reinforced plastic, or adhesive using Fiber Bragg Grating (FBG) sensors embedded in a host material is shown. Different features of the crack mechanism that induce a change in the FBG response were identified. Double Cantilever Beams specimens made with glass fibre glued with structural adhesive, were instrumented with an array of FBG sensors embedded in the material and tested using an experimental fracture procedure. A digital image correlation technique was used to determine the presence of the specific phenomena caused by the crack, and to correlate with the FBG sensor. An algorithm was developed that analyses the reflected peak at each measurement time, and calculates the contribution of each fracture phenomenon to the change in the FBG response. This Material-Sensor model was implemented in a Finite Element Method (FEM) Model of the DCB specimen, to simulate the response of the FBG sensor during the process of crack growth, proving that this Material-Sensor model can be used as an analysis tool for future application of this measurement technology in more complex structures.

***Keywords**:* Fibre Bragg Grating Sensors, Crack Growth Monitoring, Fibre Reinforced Plastic Crack Monitoring, Digital Image Correlation.

INTRODUCTION

Fibre Reinforced Plastic materials (FRP or as often called composite materials) have been extensively used in several engineering fields and applications, such as, aerospace, automotive, naval, civil engineering and wind energy. The rapid growth of the FRP material is mostly due to its high weight-stiffness ratio when compared with other conventional materials, like steel. The FRP material consist of two macroscopic phases, a stiff fibre phase, usually glass or carbon fibre, and polymeric matrix, usually polyester or epoxy. The main advantage of this material is that the alignment of the fibres can be arranged to suit the required properties of the intended structure. Taking a wind turbine blade as an example, the requirement for a stiff (but light-weight) structure means fibre orientation primarily along the length of the blade; however in the axial direction this stiffness requirement is much lower, meaning that less material is required and used to reinforce in this direction. In sum, the FRP materials can be tailored to a specific application, and obtain a high level of customization of mechanical properties, such as weight-stiffness ratio, thermal expansion, chemical/corrosion resistance, fatigue behaviour, etc. [**1**].

However, the increasing demand for more cost-effective lightweight composite materials is pushing for advances in material technology, design philosophies and monitoring techniques, as well as requiring a deeper understanding of their failure mechanisms. Damage tolerant design is a developing design concept where the structure/material capability to hold damage is taken into consideration during the process design. If this concept is incorporated with a structural health monitoring system over the design and operation of a structure, this will enable safe operation despite the presence of damage, such as that created by fatigue, intrinsic/discrete damage, manufacturing defects or accidental damage that can occur. In addition, this approach will enable a "real time" reactive maintenance of the structure.

Based on this, the authors approach for a successful damaged tolerance design is based not only on accepting the presence of damage in a structure, but by controlling it and using the full mechanical capability of the material and structure during the evolution of the damage. This will require integrated sensors that give information about the presence of damage in an accurate way, its location and the type of damage [**2**]. As delamination is one of the most important failure mechanisms in FRP materials, and one of the most widespread causes of FRP structure life reduction, in this study a novel method to assess cracking in FRP materials using embedded Fiber optic Bragg Grating (FBG) sensor was developed, by measuring specific phenomenon that only appear in the presence of a crack.

FIBER OPTIC BRAGG GRATING SENSOR

Different sensing technology has been implemented in FRP material structures to track delamination and cracks. Acoustic emission that measures the stress waves generated by the crack front growing, vibration that detects changes in the specific damping capacity of the structure, model analysis by monitoring the materials natural frequencies and mode shapes, piezo-electric actuators/sensors and wavelet analysis based on the energy variation of the structural dynamic. However, these measurement systems have several limitations, among these the need for qualified operators, expensive hardware and that they are often impractical to use under operation. Also, to detect delamination in FRP materials the sensor must be embedded in the laminate layers or in the interface of the FRP and a structural adhesive.

Fibre Bragg Gratings (FBG) are a very promising technology to detect delamination in an operational FRP structure, due to their capability to be embedded in the FRP material, even in an operational structure, without compromising its structural resistance. This is due to the FBG reduced size, with a diameter of 125 μm, which makes it a virtually non-intrusive sensing technique. The FBG sensors, also presents other interesting features, such high strain resolution, multiplexing capability, immunity to electromagnetic fields, chemical inertness and long term stability [**3**].

<u>Fiber Bragg Grating Working Principal</u>

A Fiber Bragg Grating is formed when a permanent periodic modulation of the refractive index is induced along a section of an optical fiber, by exposing the optical fiber to an interference pattern of intense ultra-violet light. The photosensitivity of the silica exposed to the ultra-violet light is increased, so when the optical fiber is illuminated by a broadband light source, the grating diffractive properties are such that only a very narrow wavelength band is reflected back [**3**]. Any external phenomenon that creates a change on the grating, like temperature, strain, compression, non-uniform strain fields, etc. will change the shape of the reflected light. Tracking this change in the reflected peak is the measurement working principal of the FBG, however, different phenomena acting on the grating will make different changes to the sensor response (like a fingerprint), and so, it will be possible to track specific phenomena that are characteristic of damage.

The spectral response of a homogeneous FBG is a single peak centred at the wavelength λ_b. The λ_b wavelength is described by the Bragg condition,

$$\lambda_B = 2n_{eff,0}\,\Lambda_{,0} \tag{1}$$

where n_0 is the mean effective where refractive index at the location of the grating, the index *0* denotes unstrained conditions (initial state). The n_{eff} is the effective refractive index and Λ is the constant nominal period of the refractive index modulation.

DELAMINATION DETECTION IN FRP DOUBLE CANTILIVER BEAM BY EMBEDDED FBG SENSOR.

To analyse the delamination in FRP material and develop a technique that can assess the presence and growth of such damage by embedded FBG sensors, Double Cantilever Beam (DCB) specimens were tested in a fracture testing machine, developed by Sørensen [**4**]. The DCB specimens were loaded with different combination of Moments, which will give different type of fracture modes, simulating different crack/delamination cases.

The DCB specimens were manufactured using two FRP material arms, made of unidirectional and triaxial glass fibre layers (SAERTEX UD and TRIAX), with a layup stacking of : [90/ +45 /-45/0_4/0_4/+45/-45/90], glued by a commercial epoxy structural adhesive (Epikote MGS BPR

135G/Epikote MGS BPH137G). A thin slip foil was placed in the edge of the structural adhesive, to act as a pre-crack and ease crack initiation.

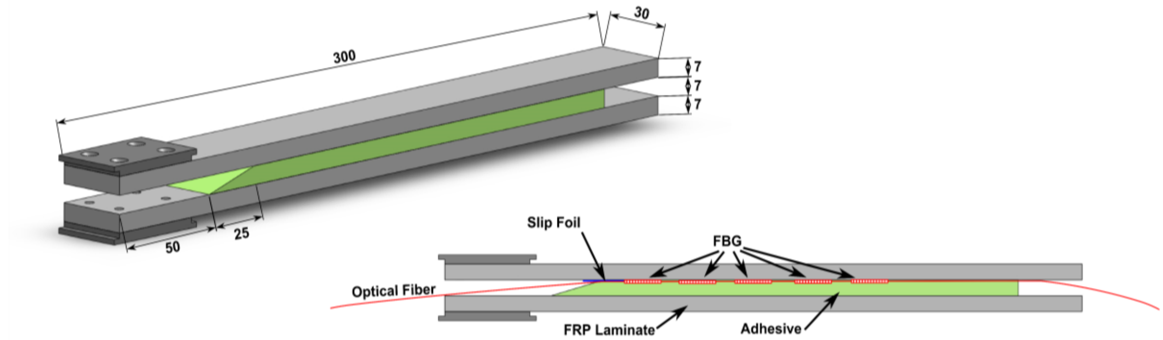

Fig. 1: DCB specimen geometry and FBG sensor array configuration.

An array of 5 uncoated single mode (SM) FBG sensors, each with a length of 10 mm, was embedded in the interface of the composite material with the structural adhesive. The gratings array were spaced by 10 mm from each other, and the first grating was positioned 10 mm from the edge of the adhesive. In figure 1, the DCB specimen dimensions and FBG sensor array configuration is presented. The sensors were connected to an Optical Spectral Analyser (OSA) *FS2200 - Industrial BraggMETER* from FiberSensing^{TM}.

To determine the presence of specific phenomena caused by the crack and to correlate this with the FBG output, a digital image correlation technique was applied to the specimens. Digital image correlation is an optical method that by tracking changes in a random pattern on the specimen gives deformation/strain information about the material. To perform this, a pattern was painted on the side surface of the DCB specimen and ARAMIS^{TM} software was used to calculate the strains at each measurement.

EXPERIMENTAL TEST ANALYSIS: DCB FRACTURE

In figure 2 and 3, the strain distribution on the surface of the DCB specimen (left pictures) and the FBG sensor output (right picture), before and during the propagation of the crack/delamination are shown. Analysing the strain evolution before the crack starts to propagate in the material, shows build-up of strain, due to the increasing load. Once the crack start to grow, a compression field is formed ahead the crack tip due to the formation of a crack bridging zone [**5**]. This compression stress area can be observed in figure 3: top left DIC measurement as a blue spot. At the same time, a decrease in the material compliance due to the growth of the crack causes a rapid local increase of strain, creating a gradient of strain near the crack tip (non-uniform strain), which can be observed in figure 3: bottom left DIC measurement.

As shown, different fracture phenomena will be present during the crack growth, being able to identify the effect on the FBG sensor response is the key factor to correctly determining the presence of damage and its growth. Next is described the effect that each one of these fracture phenomena have on the FBG Response.

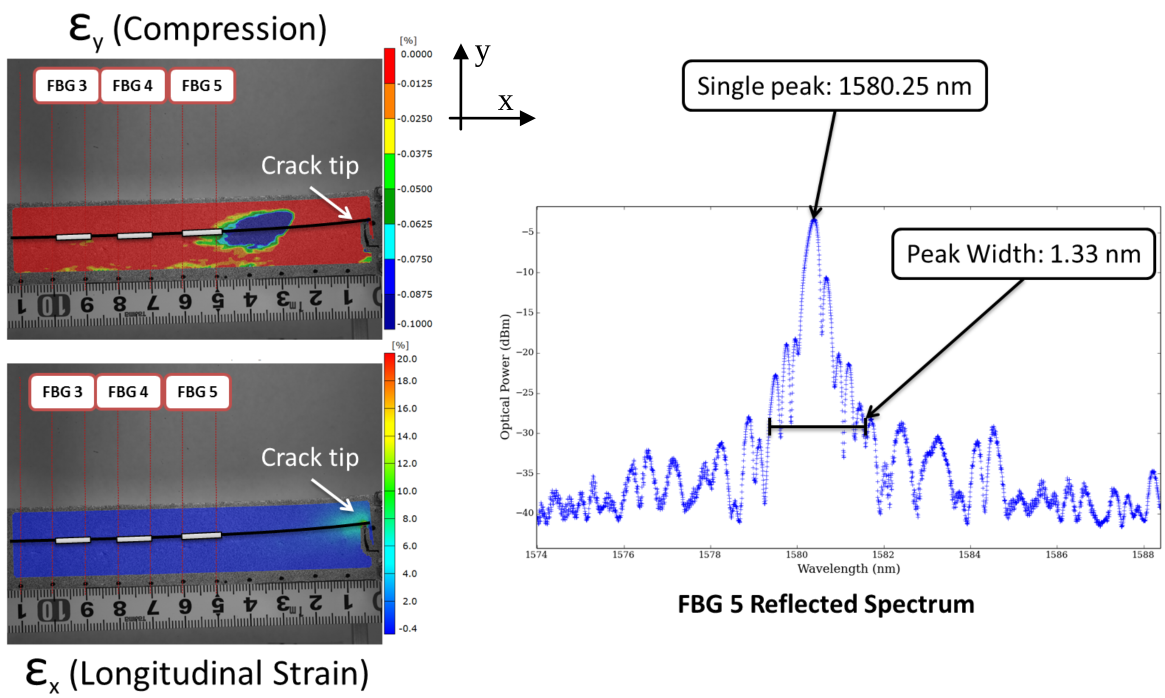

Fig. 2: FBG sensor output and DIC measurement before crack growth.

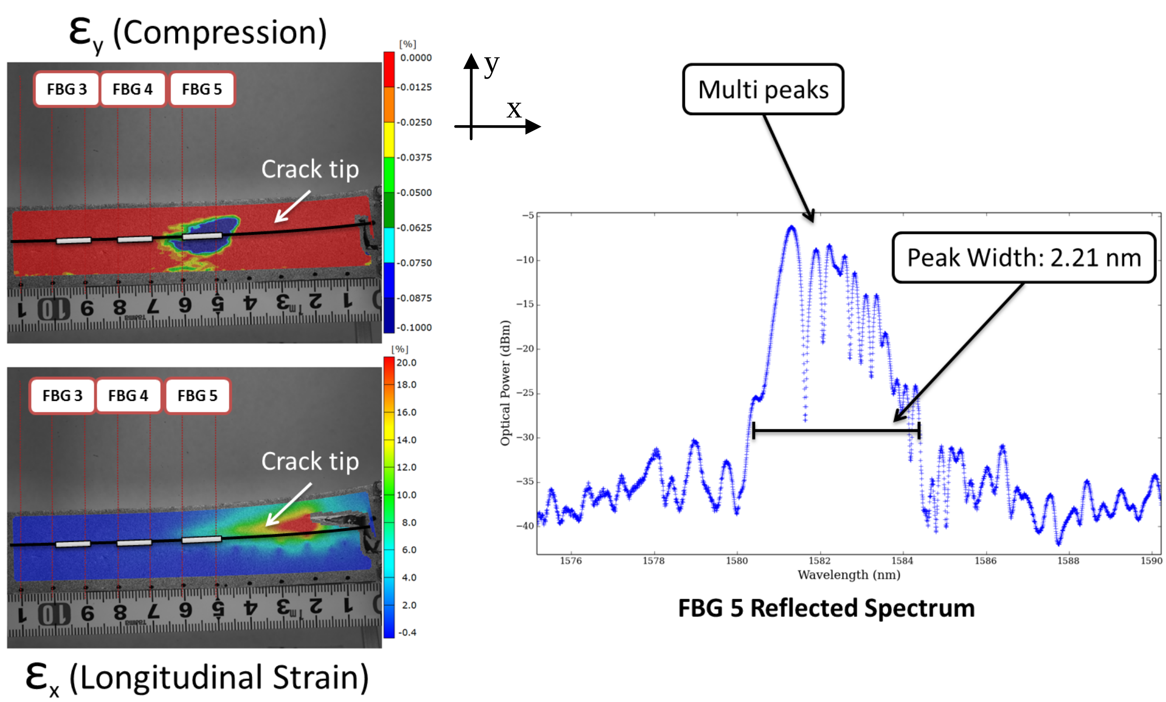

Fig. 3: FBG sensor output and DIC measurement during crack growth.

FBG RESPONSE DURING CRACK GROWTH

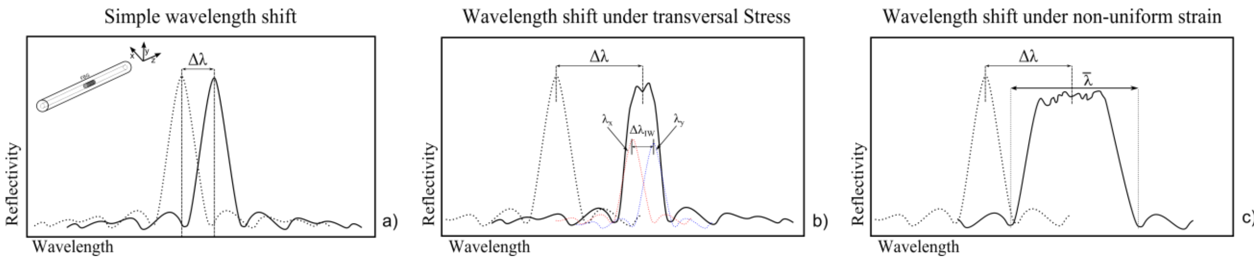

Fig. 4: FBG response during crack growth.

FBG response: Uniform Strain

As described, before the crack starts to grow, the material will build-up uniform strain, which will interact with the FBG by deforming it uniformly. This will create a wavelength shift in the FBG reflected peak, as showed in Figure **4a).**

The wavelength shift $\Delta\lambda_b$ of an embedded FBG under a uniform variation of strain, ε_{zz}, along the fibre direction, and considering no temperature variation (during crack growth temperature variation is neglected), is given by the equation 2,

$$\frac{\Delta\lambda_b}{\lambda_b} = (1 - pe)\,\varepsilon_{zz} \qquad (2)$$

where *pe* is the photoelastic coefficient of the optical fibre.

FBG response: Transverse Stress

During the crack growth, the compression field formed ahead of the crack tip will reach the grating area, which will create a peak split of the FBG reflected signal. This peak split phenomenon is due to a birefringent effect, observed in figure **4b)** and figure **3**. The birefringent behaviour is defined by the change of the refractive index n_{eff} in the two directions n_{effy} and n_{effx}, when the grating is subjected to a transverse force **[6]**. The increase in the width of the reflected peak represented in figure **4b)**, is given by the equation 3,

$$\Delta\lambda_{WV} = 2\Lambda\left|\Delta n_{effz} - \Delta n_{effy}\right| = \frac{\Lambda n_0^3}{E_f}\left[(1+\upsilon_f)p_{12} - (1+\upsilon_f)p_{11}\right]\left|\sigma_x - \sigma_y\right| \qquad (3)$$

where $\sigma_{x,y}$ is the transverse stress, E_f is the elastic modulus of the optical fibre, v_f is the Poisson's ration, n_0 is the initial refractive index, p_{11} and p_{12} are the photo-elastic coefficients of the optical fibre.

FBG response: Non-Uniform Strain

When the grating is near the influence of a high strain gradient (non-uniform strain), the shape of the reflected peak is changed, as observed in figure **4c)** and figure **3**. The non-uniform strain changes the periodicity of the grating pattern along the sensor length, modifying the grating pattern configuration from "uniform" to "chirped". As demonstrated by Peters [**7**], in a uniform grating the applied strain will induce a change in both grating period and the mean index. These two effects can be superimposed by applying an effective strain of "$(1-pe)\varepsilon_{zz}(z)$", similar the first part of equation 2, but taking into account the strain variation along the z direction. Then it is possible to rewrite the grating period as:

$$\Lambda(z) = \Lambda_0\left[1 + (1 - pe)\varepsilon_{zz}(z)\right] \tag{4}$$

where Λ_0 is the grating period with zero strain. The non-uniform strain effect can be approximated by using the maximum and minimum strain values along the grating. So, the maximum grating period Λ_{max} and minimum Λ_{min} can be calculated using the equation 1. Thus, an approximated increase of the width of the reflected peak due to a non-uniform strain $\bar{\lambda}$ is given by combining equations 4 and equation 1:

$$\bar{\lambda} = 2n_{eff}\Lambda_{\max} - 2n_{eff}\Lambda_{\min} \tag{5}$$

ALGORITHM FOR CRACK DETECTION USING FBG SENSORS

The DIC technique measurements showed that specific fracture phenomena formed near the crack, as such as the compression field and the non-uniform strain, will create a change in the shape of the reflected peak by increasing its width and creating a peak splitting. Thus, it is required to extract this information independently from the sensor response, in order to become possible to determine the presence of a crack and it growth. To do this, an algorithm was developed that analyses the reflected peak at each measurement time, and calculates the contribution of each fracture phenomenon in the change of the FBG response.

The algorithm was implemented using Python language, and uses the raw data from the Optical Spectral Analyser to compute the wavelength shift $\Delta\lambda_b$, the number of reflected peaks, and the width increase of the reflected peak $\Delta\lambda_{WV}$. To calculate the wavelength shift $\Delta\lambda_b$, the algorithm detects the maximum reflected optical power of each grating, and then computes $\Delta\lambda_b$ in relation to the original reflected peak. In case that the reflected peak is distorted, or showing a split shape, the algorithm interpolates $\Delta\lambda_b$ between the maximum points in the grating bandwidth and the last maximum peak, before the split occur. To calculate the width of the reflected peak $\Delta\lambda_{WV}$, the algorithm determines the maximum and minimal reflected optical power for each grating, and measure the peak width at half maximum optical power ((maximum+minimal)=2). Then, it computes the width variation of the reflected peak $\Delta\lambda_{WV}$ in relation with the original reflected peak width. After $\Delta\lambda_b$ and $\Delta\lambda_{WV}$ been computed, the algorithm calculate the strain $\varepsilon_{zz,}$ the non-uniform strain $\varepsilon_{zz\ (z)}$ and the compression stress $\sigma_{x,y}$ in each grating location, as showed in figure 5.

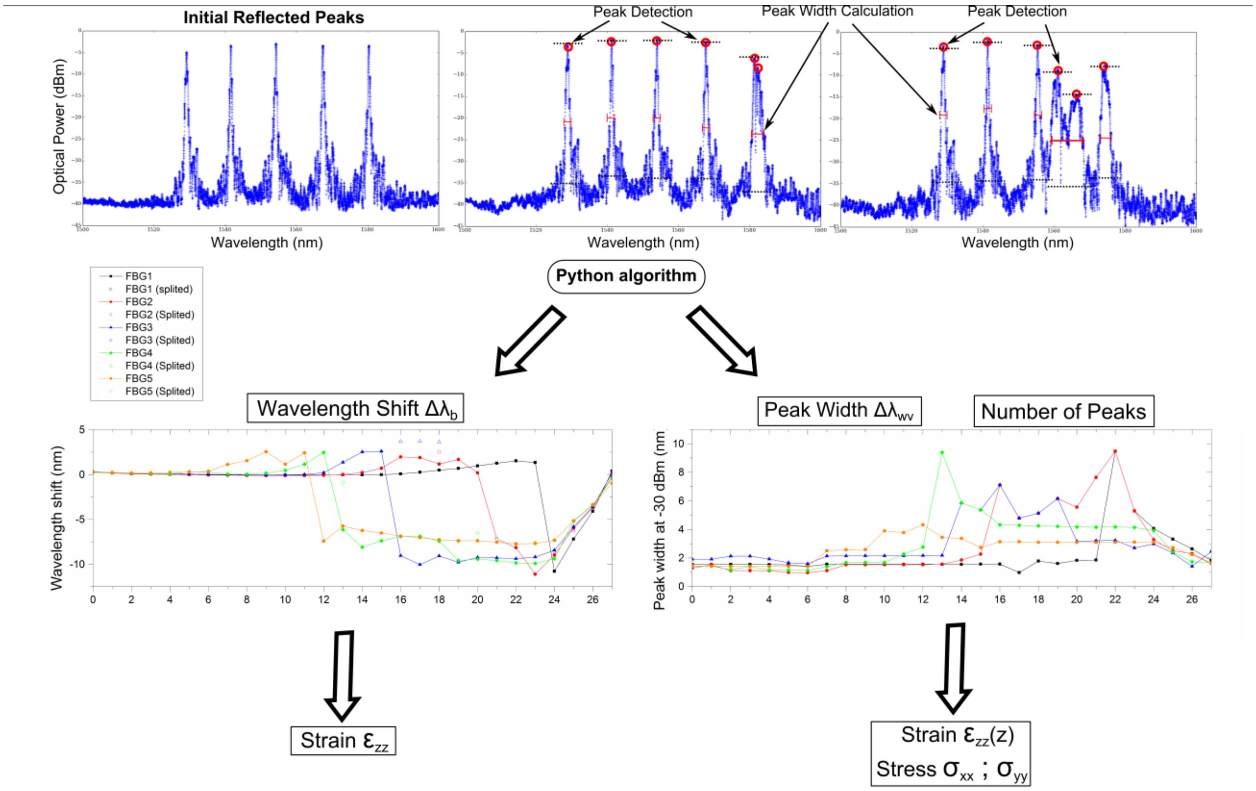

Fig. 5: Algorithm for crack detection using FBG sensors.

APPLICATION OF THE FBG CRACK DETECTION METHOD

By using this method it becomes possible to extract two types of information from the sensor: one type that are dependent of the loading and geometry, ε_{zz}, which give information about the global strain/loading state of the structure; The other type, ε_{zz} (z) and $\sigma_{x,y}$, are independent and only affected by the proximity of a crack.

To show the applicability of this technique to other structures or materials, this monitoring method was implemented in a Finite Element Method (FEM) Model of the DCB specimen, which simulates the response of the FBG sensor during the process of the crack growth. In figure 6 the application of the FBG crack detection method in the delamination of a DCB specimen together with a simulation of damage growth in a wind turbine trailing edge is showed.

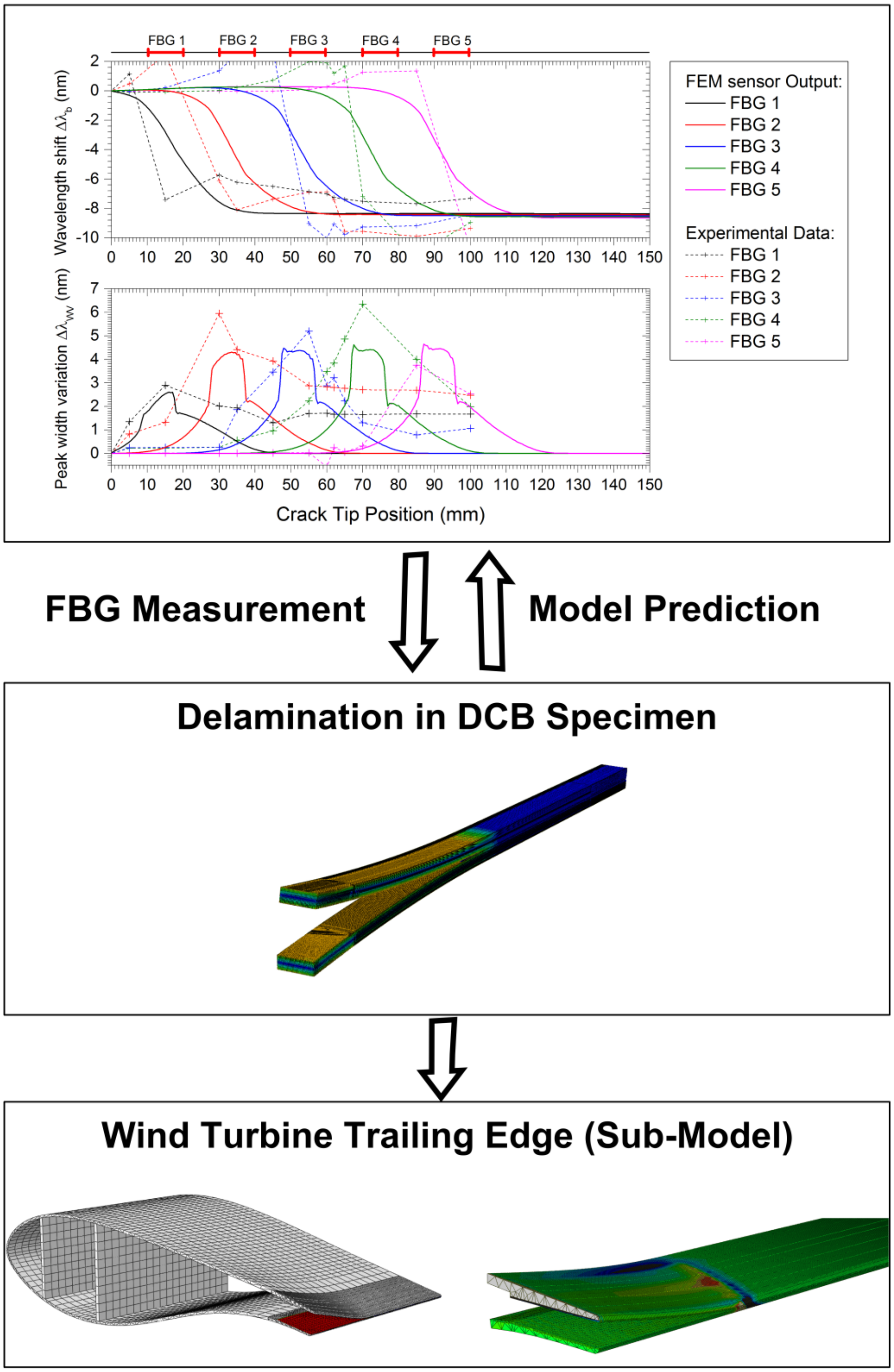

Fig. 6: Application of the FBG crack detection method in a DCB specimen and Wind Turbine trailing edge.

CONCLUSION

In this article the capability of Fibre Bragg Gratings embedded in composite material to detect and track cracks/delamination was demonstrated. The use of the digital image correlation technique proved that specific fracture features near the crack can create a change in the shape of the reflected peak. Thus, it is possible to extract information from the sensor that is independent of the loading type, geometry and boundary conditions, and depends only on the proximity of the crack. This fact allows the application of this technique in general composite material structures.

The wavelength shift is dependent on the loading type, but the increase in the width of the peak is related to the presence of the crack (Birefringent effect and non-uniform strain). Using this information it is possible to track the crack by an abrupt variation of the wavelength and/or increase in the width of the reflected peak. This monitoring method can be implemented in a structural model using the equations developed. This makes it possible to study the application of this monitoring technique in other locations, predict the sensor output and determine the optimized sensor-structure configuration.

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